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**PROVISIONAL SPECIFICATION**

Invention Title: "NOVEL PHOTOELECTRICHEMICAL  
OXYGEN DEMAND ASSAY"

The invention is described in the following statement:

## NOVEL PHOTOELECTROCHEMICAL CHEMICAL OXYGEN DEMAND ASSAY

### FIELD OF THE INVENTION

5 THE INVENTION RELATES TO a new method for determining oxygen demand of water using photoelectrochemical cells. In particular, the invention relates to a new photoelectrochemical method of determining chemical oxygen demand of water samples using a titanium dioxide nanoparticulate semiconductive electrode.

### BACKGROUND TO THE INVENTION

#### 10 OXYGEN DEMAND ANALYSIS METHODOLOGIES

Nearly all domestic and industrial wastewater effluents contain organic compounds, which can cause detrimental oxygen depletion (or demand) in waterways into which the effluents are released. This demand is due largely to the oxidative biodegradation of organic compounds by naturally occurring microorganisms, which utilize the organic material as a food source. In this process, carbon is oxidised to carbon dioxide, while oxygen is consumed and reduced to water.

Standard analytical methodologies for the determination of aggregate properties such as oxygen demand in water are biochemical oxygen demand (BOD) and chemical oxygen demand (COD). BOD involves the use of heterotrophic microorganisms to oxidise organic material and thus estimate oxygen demand. COD uses strong oxidising agents, such as dichromate or permanganate, to oxidise organic material. BOD analysis is carried out over five days and oxygen demand determined by titration or with an oxygen probe. COD measures dichromate or permanganate depletion by titration or spectrophotometry.

Despite their widespread use for estimating oxygen demand, both BOD and COD methodologies have serious technological limitations. Both methods are time consuming and very expensive, costing water industries and local authorities in excess of \$1 billion annually worldwide. Other problems with the BOD assay include: limited linear working range; complicated, time consuming procedures; and questionable accuracy and

reproducibility (the standard method accepts a relative standard deviation of  $\pm 15\%$  for replicate BOD<sub>5</sub> analyses). More importantly, interpretation of BOD results is difficult since the results tend to be specific to the body of water in question, depend on the pollutants in the sample solution and the nature of the microbial seed used. In addition, the BOD methodologies cannot be used to assess the oxygen demand for many heavily polluted water bodies because of inhibitory and toxic effects of pollutants on the heterotropic bacteria.

The COD method is more rapid and less variable than the BOD method and thus preferred for assessing the oxygen demand of organic pollutants in heavily polluted water bodies. Despite this, the method has several drawbacks in that it is time consuming, requiring 2-4 hours to reflux samples, and utilises expensive (e.g. Ag<sub>2</sub>SO<sub>4</sub>), corrosive (e.g. concentrated H<sub>2</sub>SO<sub>4</sub>) and highly toxic (Hg(II) and Cr(VI)) reagents. The use of toxic reagents being of particular environmental concern, leading to the Cr(VI) method being abandoned in Japan.

#### PHOTOOXIDATION BY TITANIUM OXIDE

Titanium(IV) oxide (TiO<sub>2</sub>) has been extensively used in photooxidation of organic compounds. TiO<sub>2</sub> is non-photocorrosive, non-toxic, inexpensive, relatively easily synthesised in its highly catalytic nanoparticulate form, and is highly efficient in photooxidative degradation of organic compounds.

Fox M.A. and Tien, T, Anal. Chem, 1988, 60, 2278-2282 investigated the development of a photoelectrochemical detector by employing an anodically formed TiO<sub>2</sub> electrode for use in high-pressure liquid chromatography. This photoelectrochemical detector is reported as being sensitive to oxidisable organics, such as alcohols. The electrode system developed by Fox et al had low photocatalytic efficiency of the system and is difficult to use as it cannot discriminate between the respective currents generated from the oxidation of water and organic matter.

Brown, G.N., et al., Anal. Chem, 1992, 64, 427-434 investigated the use of a photoelectrochemical detector by employing a thermally formed

TiO<sub>2</sub> electrode in flow injection analysis and liquid chromatography. The detector was found to be non-selective in its response to a variety of organic analytes. Brown et al found that the response of the detector varied with temperature, duration of heating, oxidative atmosphere, etching of the titanium wire electrode, amount of doping on the TiO<sub>2</sub> detector and solvents. Similar to Fox et al this electrode system had low photocatalytic efficiency and cannot discriminate between the currents generated from the oxidation of water and organic matter.

Matthews R.W. et al., *Analytica Chimica Acta* 233 (1990) 171-179 (also the subject of Australian patent 597165) utilised a TiO<sub>2</sub> photocatalytic oxidation system to determine total carbon in water samples, by placing TiO<sub>2</sub> into a slurry or suspension, photooxidising the organic material with in the sample to evolve carbon dioxide CO<sub>2</sub>. The evolved CO<sub>2</sub> volume was measured using a TOC analyser. Matthews found that the total carbon can be determined from the total volume of carbon dioxide purged from photocatalytic cell.

Jiang D. et al., *J. Photochem & Photobio A: Chemistry* 144 (2001) 197-204 also investigated the photoelectrochemical behaviour of nanoporous TiO<sub>2</sub> film electrodes in the photooxidation of methanol. Jiang found that the photoresponse of the electrode was greatly influenced by applied potential, light intensity, methanol concentration and pH. A linear relationship was found to exist between the photocurrent produced through the photo-oxidation of methanol and the concentration of methanol in the sample. However, as concentration of methanol increased the migration of photoelectrons across the TiO<sub>2</sub> film and therefore photogenerated charge separation becomes a rate-limiting step, thus limiting the working range in which the linear relationship between photocurrent and concentration occurs.

Lee Kyong-Hoon et al., *Electroanalysis* 12, No 16 (2000) 1334-1338, investigated the determination of COD using a microfabricated Clark-type oxygen electrode and TiO<sub>2</sub> fine particles suspended in a sample solution under photocatalytic oxidative degradation conditions. The current generated from the oxygen electrode under -800mV applied potential was

used to indicate the oxygen concentration change before and after the photooxidation. The change in oxygen concentration was then correlated to COD value of the sample.

Kim, Yoon-Chang, et al., Anal. Chem, 2000, 74, 3379-3362; Analytica Chimica Acta 432 (2001) 59-66 and Anal. Chem, 2002, 74, 3858-3864 all relate to the determination of COD using a photocatalytic oxidative degradation of organic compounds at a titanium dioxide particles. In Anal. Chem, 2000, Kim et al investigated the use of translucent poly(tetrafluoroethylene) (PTFE) membrane having fine particles of  $\text{TiO}_2$  absorbed or entrapped onto the surface of the membrane in combining with a oxygen electrode as a possible COD sensor. The immobilised  $\text{TiO}_2$  particles serve as an oxidation reagent and the analytical signal was based on the oxygen concentration measurements between the working and reference oxygen electrodes. Calibration curves were established using sodium sulfite ( $\text{Na}_2\text{SO}_3$ ), prior to determining COD of analytes. In this study Kim et al reports that the membrane sensor did not show good reproducibility.

In Analytica Chimica Acta 432 (2001) 59-66, Kim et al investigated the use of titanium dioxide ( $\text{TiO}_2$ ) beads in a photochemical column and an oxygen electrode as the sensor in determining dissolved oxygen from the photocatalytic oxidation of organic compound and thus the COD value of the analyte.

In Anal. Chem, 2002, 74, 3858-3864, Kim et al investigated the use of 0.6mm  $\text{TiO}_2$  beads in a quartz tube in the determination of oxygen consumption from photochemical oxidation of organic compounds and subsequent calculation of COD values from the difference in the currents recorded at the reference and working oxygen electrodes.

The methods described by Lee et al and Kim et al above all utilise  $\text{TiO}_2$  as an oxidative reagent to replace the traditional reagent used in COD such as chromate salts, with the analytical signal being obtained via two traditional oxygen electrodes.

To date the COD assay methodologies of the prior art are indirect in

their analysis methods and often suffer from having low sensitivity, poor accuracy, narrow linear working ranges and/or difficult to operate.

#### SUMMARY OF THE INVENTION

In one form, although it need not be the only or indeed the broadest form, the invention resides in a method of determining chemical oxygen demand of a water sample in a photo electrochemical cell, comprising the steps of;

applying a constant potential bias to the photoelectrochemical cell, having a nanoparticulate semiconductive working electrode and a counter electrode, and containing a supporting electrolyte solution;

illuminating the working electrode with a light source and preferably a UV light source and recording the background photocurrent produced at the working electrode from the supporting electrolyte solution;

adding a water sample, to be analysed, to the photoelectrochemical cell;

illuminating the working electrode with a light source and preferably a UV light source and recording the total photocurrent produced and

determining the chemical oxygen demand of the water sample according to the type of degradation conditions employed.

The method of determining the chemical oxygen demand value of a water sample may be determined under exhaustive degradation conditions, in which all organics present in the water sample are oxidised. Under exhaustive degradation conditions the chemical oxygen demand value can be obtained according to the steps of;

a) integrating both the background photocurrent and total photocurrent to give the background charge and total charge, and subtracting the background charge from the total charge to determine the net charge  $Q_{net}$ ; for the water sample; and

b) calculating the chemical oxygen demand value utilising formula (I);

$$COD \text{ (mg / L of } O_2) = \frac{Q_{net}}{4FV} \times 32000 \quad (I)$$

wherein  $Q_{\text{net}}$  = net charge  
 $F$  = Faradays constant  
 $V$  = sample volume

5 The method of determining the chemical oxygen demand value of a water sample may be determined under non-exhaustive degradation conditions, in which the organics present in the water sample are partially oxidised. Under non-exhaustive degradation conditions, all photocurrent are measured under the diffusion controlled conditions and the method of determining oxygen demand value may further include the steps of;

10 adding a standard solution, having known organic concentration or chemical oxygen demand value, to the photoelectrochemical cell containing the water sample to be analysed;

illuminating working electrode with a UV light source and recording the limiting photocurrent produced from the partial oxidative degradation of the standard solution ( $i_l(2)$ ); and

determining the chemical oxygen demand value by;

a) calculating the current for the water sample by subtracting the limiting background photocurrent ( $i_{l\text{background}}$ ) from the limiting photocurrent of the sample ( $i_l(1)$ ) at a predetermined illumination time according to the formula

$$i_{\text{sample}} = i_l(1) - i_{l\text{background}}$$

b) calculating the limiting photocurrent for the standard solution by subtracting the background photocurrent ( $i_{l\text{background}}$ ) from the limiting photocurrent of the sample and standard ( $i_l(2)$ ) at the predetermined illumination time according to the formula:

$$i_{\text{standard}} = i_l(2) - i_{l\text{background}}$$

c) determining the chemical oxygen demand value of the sample solution according the following sequence of computations:

$$i_{\text{sample}} = nFAk [\text{COD}]_{\text{sample}} = K[\text{COD}]_{\text{sample}}$$

$$i_{\text{standard}} = nFAk\{[COD]_{\text{sample}} + [COD]_{\text{standard}}\} = K\{[COD]_{\text{sample}} + [COD]_{\text{standard}}\} \text{ where}$$

$K = nFAk$  is a constant for given experimental conditions

$n$  = number of electrons transferred during the  
photoelectrochemical degradation,

5

$F$  = Faraday constant,

$A$  = active electrode area,

$k$  = mass-transfer coefficient; and

$$[COD]_{\text{sample}} = \frac{i_{\text{sample}}}{i_{\text{standard}} - i_{\text{sample}}} \times [COD]_{\text{standard}}$$

10 The method steps for both the exhaustive and non-exhaustive degradation condition may be repeated as many times as required to analyse all necessary water samples.

The potential bias applied to the electrodes is preferably between -0.1V and 0.5V. More preferably the potential difference is between approximately +0.15V and +0.35V.

15

The supporting electrolyte may be selected from sodium nitrate, sodium perchlorate or any other electrolytes that electrochemically and photoelectrochemically stable under the experimental conditions.

20 The water sample is preferably illuminated by a light source having a photo intensity of between 5 and 100 mWcm<sup>-2</sup>. More preferably the frequency of the light source is between approximately 8 – 9.5mWcm<sup>-2</sup>.

25 Preferably the nanoparticle semiconductive electrode is any nanoparticulate semiconductor capable of photocatalytic oxidation of organic compounds or materials. The nanoparticulate semiconductive electrode may be selected from titanium dioxide, niobium pentoxide, strontium titanate, indium trioxide, calcium titanate, tungsten trioxide, barium titanate, ferric oxide, zinc oxide, potassium tantalate, tin dioxide, cadmium oxide, hafnium oxide, zirconium oxide, tantalum pentoxide, chromium trioxide or yttrium trioxide. Preferably the semiconductive electrode is titanium dioxide. More preferably the semiconductive electrode is formed by laying nanoparticles of

**titanium dioxide on an inert substrate, such as conducting glass.**

### BRIEF DESCRIPTION OF DRAWINGS

To assist in understanding the invention preferred embodiments will now be described with reference to the following figures in which:

- |    |         |  |
|----|---------|--|
| 5  | Fig. 1. | Schematic of the instrumentation of photoelectrochemical detection system.   |
|    | Fig. 2. | Schematic diagram of the photoelectrochemical batch cell.  |
|    | Fig. 3. | Schematic diagram of the thin-layer photoelectrochemical flow cell.  |
| 10 | Fig. 4. | FIA Manifold of automatic COD photoelectrochemical detector.   |
|    | Fig. 5. | Graphical representation of non-exhaustive degradation, current/time profiles of supporting electrolyte, sample and standard solutions.  |
| 15 | Fig. 6. | Photocurrent response of a solution containing 40 $\mu$ M of potassium hydrogen phthalate and 0.1M NaNO <sub>3</sub> . Photo intensity: 9.1mWcm <sup>-2</sup> ; Applied potential bias: +0.20V vs Ag/AgCl.                       |
|    | Fig. 7, | i <sub>t</sub> -C curves for a range of organic compounds, namely;   |
| 20 |         | 1 = p-chlorophenol;                  2 = potassium hydrogen phthalate;   |
|    |         | 3 = methanol;                        4 = d-glucose;  |
|    |         | 5 = malonic acid;                  6 = succinic acid;  |
|    |         | 7 = glutaric acid; and              8 = glycine.   |
|    |         | Photo intensity: 9.1mWcm <sup>-2</sup> ; Applied potential bias: +0.20V vs Ag/AgCl.  |
| 25 | Fig. 8. | Photocurrent response of (a) 0.10M NaNO <sub>3</sub> and (b) a solution containing potassium hydrogen phthalate and 0.1M NaNO <sub>3</sub> . Photo intensity: 9.1mWcm <sup>-2</sup> ; Applied potential bias: +0.20V vs Ag/AgCl. |
|    | Fig. 9. | Q -C curves for a range of organic compounds, namely;  |
| 30 |         | 1 = p-chlorophenol;                  2 = potassium hydrogen phthalate;   |
|    |         | 3 = methanol;                        4 = d-glucose;  |
|    |         | 5 = malonic acid;                  6 = succinic acid;  |

7 = glutaric acid; and 8 = glycine.

Photo intensity:  $9.1 \text{ mWcm}^{-2}$ ; Applied potential bias: +0.20V vs Ag/AgCl.

5 Fig 10. Correlation between experimental COD value and standard COD value. (a) COD standard test solution (KHP); (b) a synthetic COD sample containing equal molar concentration of all compounds used in Figure 8.

10 Fig. 11. Comparison of photoelectrochemical detection and conventional COD method (dichromate) in the detection of real samples.

#### DETAILED DESCRIPTION OF THE INVENTION

15 The assay method of the invention takes advantage of the highly efficient photochemical properties of  $\text{TiO}_2$  nanoparticulate film electrodes to develop a new, rapid, cost-effective assay for the determination of aggregate organic properties, such as oxygen demand and in particular COD.

20 The below description is directed to a method of determining chemical oxygen demand of water samples utilising a nanoparticulate  $\text{TiO}_2$  film electrode. It will be appreciated by the person skilled in the art that other nanoparticulate semiconductive film electrode may be utilised in the method without departing from the essence of the invention.

The assay method of the invention allows for easy quantification of electron transfer at a  $\text{TiO}_2$  nanoparticle film electrode during photocatalytic oxidative degradation of organic material. This approach overcomes many of the current problems with existing oxygen demand techniques.

25 In addition the mathematical derivation involved in arriving at the assay method as found that upon determination of the limiting photocurrent of a sample there is a direct correlation to the concentration of the analyte or organic compound of analysis, thus lending of the invention to application as a "universal" analytical detection system, such as HPLC, UV Vis, FIA and the  
30 like, for chemical analysis in a wide range of application areas.

### MATHEMATICAL DERIVATION

The method of determining chemical oxygen demand of water samples, according to the invention, utilises photoelectrochemical current (or charge) generated from photoelectrochemical oxidative degradation of organic compounds as an analytical signal.

The photocatalytic degradation efficiency at  $\text{TiO}_2$  depends on the degree of recombination of photoelectrons and holes. With traditional  $\text{TiO}_2$  photocatalysis systems, this relies on how fast the photoelectrons and holes are consumed by the adsorbed species.

A  $\text{TiO}_2$  nanoparticulate film electrode is used as the working electrode in a three-electrode photoelectrochemical cell. By applying an appropriate potential bias to the working electrode, it becomes more favourable for the photoelectron to be transferred to the working electrode rather than to the adsorbed  $\text{O}_2$ . The photoelectrons are subsequently forced to pass into the external circuit and to the counter electrode, where the reduction of oxygen (or other species) takes place. The photocurrent (or charge) is monitored and gives a direct measure of the oxidation of organic compounds. In effect the assay shunts photoelectrons through the external circuit to quantify the extent of oxidative degradation.

Separation of the oxidative and reductive half-reactions (Eqn.s 1 and 2, below) by imposing the electrochemical potential suppresses the recombination of photoelectrons and holes. As a result, the degradation efficiency is enhanced. In addition it has been found that the rate of degradation of organic materials is independent of  $\text{O}_2$  concentration as the rate of reduction at the counter electrode will never be the rate-limiting step of the overall degradation process. Thus overcoming the prior art problem of oxygen reduction being a rate-limiting step in the photooxidation of organic material.





### Quantification of analytical signal

The photoelectrochemical system described above can be used for two different degradation models – exhaustive and non-exhaustive degradation.

- 5 With exhaustive degradation, 100% of the organic analyte in the sample is consumed; with non-exhaustive degradation, only a small fraction of available analyte is consumed and its concentration in the bulk solution remains essentially unchanged. The former is analogous to bulk electrolysis in which all of the analyte is electrolysed and Faraday's Law is used to
- 10 quantify the concentration by measuring the charge passed; the latter is analogous to amperometric methods where the analytical signal (i.e. current) is dependent on the rate of mass transfer to the electrode surface. In our case, however, the charge/current produced is the result of photoelectrochemical processes.

- 15 When the exhaustive degradation model is employed, the charge (Q) can be measured by the integration of photocurrent within the degradation period. The analytical principle can be established using Faraday's Law:

$$Q = \int i dt = nFN = nFVC \quad (3)$$

- where:
- 20  $N$  = number of moles of analyte in the sample,  
 $n$  = number of electrons transferred during the photo-electrochemical degradation,  
 $F$  = Faraday constant,  
 $V$  = sample volume; and  
 $C$  = analyte concentration.

- 25 Since  $TiO_2$  oxidises organic compounds to the fully oxidised form of carbon (i.e.  $CO_2$ ), the value  $n$  for a given compound will be a constant. Eqn 3 can therefore be used to quantify the analyte concentration.

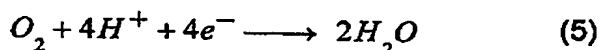
In principal, analytically useful photocurrents (or charge) can be obtained from any photo-electrochemically degradable species. The  $TiO_2$

system proposed is capable of oxidising nearly any organic or low redox state inorganic species (e.g.  $\text{Fe}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{NH}_4^+$ ,  $\text{NO}_2^-$ ). In this respect, the proposed system can be employed as a "universal" detector capable of detecting any compounds that can be photoelectrochemically oxidised at a  $\text{TiO}_2$  electrode. In combination with an appropriate separation system (e.g. HPLC), the concentration of individual analytes can be determined.

In terms of general water quality issues and pollution control, the effect and quantification of aggregate mixtures of organics (such as in COD or BOD analysis) are often more important than the analysis of single species. The proposed photoelectrochemical system is capable of determining such aggregate properties by summing the charge measured from individual photo-electrochemically degradable compounds within a mixture (Eqn 4).

$$Q = \int i dt = FV \sum_{i=1}^m n_i C_i \quad (4)$$

The measured charge,  $Q$ , is simply the total amount of electron transfer that results from the degradation of all compounds in the sample. Given that oxidation by  $\text{O}_2$  can be represented as:



where one oxygen molecule is equivalent to 4 electrons, the measured  $Q$  value can be easily converted into an equivalent  $\text{O}_2$  concentration (or oxygen demand) value:

$$\text{Equivalent Oxygen Concentration (mole / L)} = \frac{Q}{4FV} \quad (6)$$

For exhaustive degradation, the equivalent COD value of the sample can therefore be represented as:

$$\text{COD (mg / L of O}_2\text{)} = \frac{Q}{4FV} \times 32000 \quad (7)$$

In the case of non-exhaustive degradation, the quantitative relationship between the photocurrent and the concentration of the analyte can be developed using a well-known semi-empirical treatment of Steady-State Mass Transfer [A. J. Bard and L. R. Faulkner, *Electrochemical*

*Methods-Fundamental and Applications*. John Wiley & Sons, Inc. New York. 2001]. Under conditions of forced convection, the rate of mass transfer ( $dN/dt$ ) to an electrode is directly proportional to the concentration gradient at the electrode surface.

$$5 \quad \left( \frac{dN}{dt} \right) = k[C_b - C_s(x=0)] \quad (8)$$

where,  $C_b$  = concentration of analyte in the bulk solution;

$C_s$  = concentration of analyte at the electrode surface;

10  $k$  = mass-transfer coefficient [A. J. Bard and L. R. Faulkner, *Electrochemical Methods-Fundamental and Applications*. John Wiley & Sons, Inc. New York. 2001] which is  $= D/\delta$ , where  $D$  = diffusion coefficient and  $\delta$  = thickness of stagnant layer.

When sufficient photo intensity and adequate potential bias are employed, and the overall process is controlled by mass transfer, then,  $C_s(x=0) \ll C_b$ , so that  $[C_b - C_s(x=0)] \approx C_b$ . The maximum rate of mass transfer, 15  $(dN/dt)_l$  is achieved and the rate of overall reaction equals:

$$\text{Rate} = \left( \frac{dN}{dt} \right)_l = kC_b \quad (9)$$

If we again assume that after photochemical oxidation the analyte is fully oxidised, then the number of electrons transferred ( $n$ ) during photoelectrochemical degradation is a constant, for a given analyte. The 20 limiting photocurrent ( $i_l$ ) can, therefore, be used to represent the rate of reaction:

$$i_l = nFA \left( \frac{dN}{dt} \right)_l = nFAkC_b \quad (10)$$

where  $A$  = active electrode area.

25 The development of equation 10, by the current inventors, leads to definition of the quantitative relationship between the limiting photocurrent and the concentration of analyte and can be regarded as the principle of analysis.

This analytical principle can again be applied to determine concentrations of individual analytes (and serve as a "universal" detection system) or to aggregate mixtures of organics (to determine properties such as COD). Whilst formula 10 above may allow for the general determination of analyte concentration, it is the application of the findings from formula (10) to the determination of COD that assists in addressing one or more of the disadvantages in the prior art methodologies. Standard analytical and mathematical techniques may be used to calculate the COD of a sample from the limiting photocurrent measured in a photoelectrochemical cell utilising a nanoparticulate  $\text{TiO}_2$  semiconductive electrode in the manner described in more detail below.

#### **METHOD OF DETERMINING COD**

##### **FORMATION OF $\text{TiO}_2$ ELECTRODE**

###### **A) Synthesis of $\text{TiO}_2$ Colloid**

A1) A mixture of 12.5ml titanium butoxide and 4ml isopropyl alcohol was added, drop-wise, to 150ml 0.1M nitric acid solution under vigorous stirring at room temperature. After the hydrolysis the slurry was heated to  $80^\circ\text{C}$  and stirred for 8h to achieve peptization. The colloid is then filtered to remove the nonpeptized agglomerates. For better crystallinity of the nanoparticles, the colloid was hydrothermally treated in an autoclave at  $200^\circ\text{C}$  for 12h. During the autoclaving sedimentation occurred, and the particles were redispersed by sonication. The particle size is in the range of 8 to 10nm as characterised by transmission electron microscopy (TEM). Water was used to adjust the final solid concentration to ca. 6% (wt) and carbowax 20M (Merck) was added to the colloid in a proportion of 1-50% of the  $\text{TiO}_2$  weight. The colloid thus obtained was used for the preparation  $\text{TiO}_2$  nanoporous film electrode.

A2) A  $16.0\text{ cm}^3$  of isopropanol (Aldrich, AR grade) and  $50.0\text{ cm}^3$  of titanium butoxide (Aldrich, AR grade) were accurately measured into a  $150\text{ cm}^3$  dropping funnel. The resulting solution was added over 15 minutes with vigorous stirring to  $600\text{ cm}^3$  of ultrapure deionized water ( $18.2\text{ M}\Omega\text{ cm}$ ) in a

conical flask. On the completion of the addition, 4.0 cm<sup>3</sup> of 70% nitric acid (AR grade) was added into the solution as a peptizing agent. The solution was immersed in a hot water bath, heated to 80°C and stirred continuously for 10 hours. Approximately 400 cm<sup>3</sup> of a white colloidal solution remained and was stored in a dark glass vessel for use. The sizes of the TiO<sub>2</sub> synthesised according to this procedure were in a range of 8 to 10 nm.

The colloidal TiO<sub>2</sub> prepared above was placed in an autoclave reactor (Parr bomb) and autoclaved for 12 hours at 200°C before concentrating on a rotary evaporator to 8% (w/w), resulting in a white semi-viscous colloidal solution. 40% TiO<sub>2</sub> weight equivalent (e.g. 1.6g in 50.0 cm<sup>3</sup> of 8% colloidal solution) of Carbowax 6,000 was added to the solution and stirred for approximately 20 minutes.

#### **B) Immobilisation of TiO<sub>2</sub> film on ITO glass**

B1) ITO (tin doped iridium oxide) conducting glass slides were used as the substrate for immobilisation of TiO<sub>2</sub> particles. To get a clean surface the ITO glass slide was pretreated by washing in turn with detergent, water, and ethanol. After the pretreatment the ITO slide was dip-coated in the above colloidal solution from A1, above. The coated slides were then calcined in a muffle furnace in air at 500 to 800°C for 0.5h to 30h. The particle size of TiO<sub>2</sub> on the films characterised by x-ray diffraction and scanning electron microscopy (SEM) is in the range of 10nm to 100nm and the rutile/anatase phase ratio is in the range of 0.1 to 50%.

B2) TiO<sub>2</sub> films were prepared in a clean room environment to minimize contamination from dust particles. TiO<sub>2</sub> colloidal coating solution, from A2 above, was stirred vigorously and subjected to the ultrasonic treatment for 20 minutes prior to a dip coating process to achieve a consistent, reproducible homogeneous mixture. The ITO slide (conducting glass) was used as the electrode substrate and was pre-treated by washing in turn with detergent, water, acetone and water, and finally dried by pure nitrogen. After pre-treatment, the ITO slide was dip-coated with the TiO<sub>2</sub> colloidal coating

5 solution using a dip coating equipment with withdrawing speeds of 0.5 – 1.5 cm/min. The coated electrodes were then calcined in a muffle furnace at 450°C for 30 minutes in air. The nanoporous TiO<sub>2</sub> films with 1µm thickness and anatase crystalline structure were obtained. The films with different thicknesses can be prepared by controlling the withdrawing speed during the dip coating.

### C) General Setup of the Photoelectrochemical System

10 Fig. 1 shows the schematic of the instrumental set up of the photoelectrochemical detection system. Illumination was carried out using a 150W xenon arc lamp light source with focusing lenses (HF-200W-95, Beijing Optical Instruments). To avoid the sample solution being heated-up by infrared light, the light beam was an UV-band pass filter (UG 5, Avotronics Pty, Limited) prior to illumination of the electrode surface. A light shutter was used to control the ON and OFF of the illumination.

15 Generally, photoelectrochemical experiments were performed in a three-electrode electrochemical cell with a quartz window for illumination. The TiO<sub>2</sub> film electrode was installed in an electrode holder with ca. 0.65cm<sup>2</sup> left unsealed to be exposed to the solution for illumination and photoelectrochemical reaction. A saturated Ag/AgCl electrode and a platinum mesh were used as the reference and counter electrodes respectively. A voltammograph (CV-27, BAS) was used for application of potential bias in steady state photocurrent measurements. Potential and current signals were recorded using a Macintosh computer (7220/200) coupled to a MacLab 400 interface (AD Instruments).

### 25 D) The measurement procedures:

#### D1) Exhaustive degradation conditions

30 **Step 1:** Once the system is set up (see Fig 1 - 4), the supporting electrolyte solution was pumped through the photoelectrochemical cell (a thin layer cell). A bias potential of +0.20 V vs a Ag/AgCl reference electrode was applied. Once the stable baseline was obtained, the pump was stoped. The photo shutter was then switched on to allow UV radiation to reach the

electrode. The photocatalytic reaction occurred and the background current-time profile can be measured (see Fig 8 curve (a)). The background current ( $i_{Background}$ ) was resulted from the photocatalytic oxidation of water. Integrating  $i_{Background}$  with time we can obtain the background charge,  $Q_{Background}$ .

**Step 2:** After the measurement of  $Q_{Background}$ , the photo shutter was switched off and a 5 $\mu$ l to 200 $\mu$ l of sample solution with appropriate concentration was injected into the photoelectrochemical cell (It is to note that the sample volume injected is depending the volume of the cell and if the concentration of organics in the sample was too high then an appropriate dilution may be required prior the injection). Once the sample injection was completed, the pump was stopped and the photo shutter was switched on. The Current-time profile was measured (see Fig 8 curve (b)). The current obtained here is the total photocurrent ( $i_{Total}$ ) that resulted from the oxidation of water and organics. Same to the above, by integrating  $i_{Total}$  with time we have the total charge,  $Q_{Total}$ .

**Step 3:** Since the background charge,  $Q_{Background}$ , is a constant for the given experimental conditions and the total charge,  $Q_{Total}$ , varied with the concentration of the sample, therefore, the net charge,  $Q_{net}$  (the shaded area shown in Fig 8) that resulted from the oxidation of organics can be obtained by subtracting the background charge from the total charge, that is:

$$Q_{net} = Q_{Total} - Q_{Background}$$

The COD value of the sample can then be calculated according to the equation (7) since in the equation,

$$COD \text{ (mg / L of } O_2) = \frac{Q_{net}}{4FV} \times 32000 \quad (7)$$

$F$  is a constant and  $V$  is known.

Repeating steps 2 and 3 to analysis next sample.

**D2) Non-exhaustive degradation conditions**

The system set up was same as described above (see Fig 1 - 4) except that a normal flow-through cell was employed to replace the thin layer cell. The measurement can be done by using a standard addition method.

5     **Step 1:**     The supporting electrolyte solution was pumped through the photoelectrochemical cell (a normal flow-through cell with cell volume of 0.5 to 2.5 ml). A bias potential of +0.20 V vs a Ag/AgCl reference electrode was applied. Once the stable baseline was obtained, the pump was stoped. The photo shutter was then switched on to allow UV radiation to reach the  
10    electrode. The photocatalytic reaction occurred and the background current-time profile can be recorded (see Figure 5 curve (a)). The background current ( $i_{background}$ ) was resulted from the photocatalytic oxidation of water.

**Step 2:**     After the measurement of  $i_{background}$ , the photo shutter was switched off and a 0.5ml to 2.5ml of sample solution with appropriate  
15    concentration was injected into the photoelectrochemical cell (It is to note that the sample volume injected is depending the volume of the cell and if the concentration of organics in the sample was too high then an appropriate dilution may be required prior the injection). Once the sample injection was completed, the pump was stopped and the photo shutter was switched on.  
20    The Current-time profile was recorded (see Figure 5 curve (b)). The current obtained here is the total photocurrent ( $i_{total}$ ) that resulted from the oxidation of water and organics.

**Step 3:**     Once the measurement of  $i_{total}$  was completed, the photo shutter was switched off and a 0.5ml to 2.5ml of sample solution containing  
25    an appropriate concentration of standard was injected into the photoelectrochemical cell. Once the sample injection was completed, the pump was stopped and the photo shutter was switched on. The current-time profile was recorded (see Figure 5 curve (c)). The current obtained here is the photocurrent ( $i_{standard}$ ) that resulted from the oxidation of water and the  
30    organics in both original sample and the added standard.

**Step 4:** After the above measurements, the COD of the sample can be calculated according to the equation (10).

5 The limiting current for each case ( $i_{l \text{ background}}$ ,  $i_{l(1)}$  and  $i_{l(2)}$ ), can be obtained by measuring the steady current value from each curve, for example, at 45s (see Figure 5). The net limiting photocurrents for the sample solution ( $i_{l(1)}$ ) and for the sample with added standard ( $i_{l(2)}$ ) can then be calculated.

*Net limiting photocurrents (or current) for the sample solution:*

$$i_{l \text{ sample}} = i_{l(1)} - i_{l \text{ background}}$$

10 *Net limiting photocurrents (or current) for the sample with standard:*

$$i_{l \text{ standard}} = i_{l(2)} - i_{l \text{ background}}$$

According to equation (10), above, we have:

$$i_{l \text{ sample}} = nFAk [\text{COD}]_{\text{sample}} = K [\text{COD}]_{\text{sample}}$$

$$i_{l \text{ standard}} = nFAk \{ [\text{COD}]_{\text{sample}} + [\text{COD}]_{\text{standard}} \} = K \{ [\text{COD}]_{\text{sample}} + [\text{COD}]_{\text{standard}} \}$$

15 where  $K=nFAk$  is a constant for a given experimental condition.

The COD value of the sample solution we have:

$$[\text{COD}]_{\text{sample}} = \frac{i_{l \text{ sample}}}{i_{l \text{ standard}} - i_{l \text{ sample}}} \times [\text{COD}]_{\text{standard}}$$

Repeat the steps 2 to 4 for the next sample.

20 It will be appreciated by the person skilled in the art that the necessary computations set out above may be automated with the appropriate programming of a personal computer.

There are a few modes with different photoelectrochemical reactor designs (i.e. online thin-layer flow cell, and batch cell) that utilise the assay methodology and are demonstrated by following examples.

25 **Example 1: Quantification of COD using photocurrent**

The photoelectrochemical experiment was performed in a three-

electrode electrochemical batch cell with a quartz window for illumination as shown in Fig. 2. The  $\text{TiO}_2$  film electrode was placed in an electrode holder with ca.  $0.65\text{cm}^2$  left unsealed to be exposed to the solution for illumination and photoelectrochemical reaction. 0.1M  $\text{NaNO}_3$  solution was used as the supporting electrolyte. A potential bias of +0.2V was applied at the electrode and limiting photocurrents were obtained for different organic compound concentrations when the current reached steady state. The limiting photocurrent differences between samples and the blank 0.1M  $\text{NaNO}_3$  solution were taken as analytical signals, which are directly linear to organic compound concentrations within diffusion control. A linear relationship between the analytical signal and COD value was then acquired after the concentration was converted into COD value.

#### **Example 2. Quantification of COD using charges**

In this case the experiment was carried out in a thin-layer photoelectrochemical cell as shown in Fig 3. A potential bias of +0.2V was applied and 2M  $\text{NaNO}_3$  was used as supporting electrolyte. Firstly, a 2M  $\text{NaNO}_3$  electrolyte solution was injected into the thin-layer photoelectrochemical cell with a syringe and a blank transient photoelectrolysis was run as a blank sample. The photocurrent-time profile was recorded until the photocurrent reached steady state. Then samples containing organic compounds and 2M  $\text{NaNO}_3$  were injected into the thin-layer cell and the sample transient photoelectrolysis was run. The photocurrent-time profile was recorded until the photocurrent attained steady state, indicating the organic compounds have been exhaustively photoelectrolysed. The cell was washed with supporting electrolyte solution between each sample injection. Integrating the photocurrent-time profile gives the photocatalytic oxidation charge. The charge difference between sample and blank transient photoelectrolysis was taken as the analytical signal, which is directly proportional to the COD value. COD value was then determined.

#### **Example 3. Quantification of COD using charges and FIA**

Besides the use of the thin-layer photoelectrochemical cell, a flow injection analysis (FIA) system was incorporated into the COD determination.

With the combination of FIA, automatic COD determination was realised. In this case, the injection of samples and cell cleaning was controlled by a FIA controlling system as shown in Fig. 4. Pump 1 achieves the blank sample (R1) injection and cell cleaning while Pump 2 does the sample injection (R2).

A potential bias of +0.2V was applied and 2M NaNO<sub>3</sub> was used as supporting electrolyte. Firstly, a 2M NaNO<sub>3</sub> electrolyte solution was pumped into the thin-layer photoelectrochemical cell by Pump 1 and a blank transient photoelectrolysis was run as a blank sample. The photocurrent-time profile was recorded until the photocurrent reached steady state. Then samples containing organic compounds and 2M NaNO<sub>3</sub> were pumped into the thin-layer cell by Pump 2 and the sample transient photoelectrolysis was run. The photocurrent-time profile was recorded until the photocurrent attained steady state, indicating the organic compounds have been exhaustively photoelectrolysed. The cell was washed with supporting electrolyte solution by Pump 1 between each sample. Integrating the photocurrent-time profile gives the photocatalytic oxidation charge. The charge difference between sample and blank transient photoelectrolysis was taken as the analytical signal, which is directly proportional to the COD value. COD value was then determined.

### Typical experimental results

Fig 6 shows a typical photocurrent-time curve obtained from a non-exhaustive photoelectrochemical degradation process. Under a constant applied potential, when the light was switched off, the residual current (dark current) was approximately zero. Upon illumination, the current increased rapidly before decaying to a steady state value. This steady state current (limiting photocurrent) consists of two current components. One is due to mass transfer limited photoelectrochemical oxidation (degradation) of the target analyte, which is directly proportional to the concentration of the analyte. The other is due to the photoelectrochemical oxidation

(decomposition) of water, which is constant at a given pH and supporting electrolyte concentration. The net limiting photocurrent,  $i_l$ , (resulting from analyte oxidation) can be readily obtained by subtraction of the photocurrent attributed to the oxidation of water from the total photocurrent.  $i_l$  can then be used for analytical purposes (Eqn 10).

Preliminary results obtained from a range of organic compounds indicate that Equation 10 is applicable to all compounds investigated (see Fig. 7, in which 1 = p-chlorophenol; 2 = potassium hydrogen phthalate; 3 = methanol; 4 = d-glucose; 5 = malonic acid; 6 = succinic acid; 7 = glutaric acid; 8 = glycine). As predicted,  $i_l$  was found to be directly proportional to the concentration of the organic compound. The slopes of the  $i_l$ -C curves (sensitivity) are determined by the mass transfer coefficient ( $k$ ) and the number of electrons transferred ( $n$ ) during the photoelectrochemical degradation.

The photocurrent-time profile of an exhaustive photoelectrochemical degradation process was found to be similar to that of the non-exhaustive degradation process except that a steady state photocurrent can only be achieved when all of the organic compounds were consumed. In this case, the steady state photocurrent was purely due to the oxidation of water and can be easily subtracted from the total current (Fig. 8). Figure 8 shows the typical photocurrent - time profiles obtained from the electrodes during an exhaustive photoelectrochemical degradation process in phthalic acid and in blank electrolyte solutions. It can be seen that the photocurrent decayed with time and then reached a steady value, which was due to the oxidation of water. It is noted that the blank photocurrent obtained from the blank electrolyte solution was purely due to the oxidation of water, while the photocurrent obtained from the electrode in phthalic acid solution consists of two current components, one is due to photoelectrochemical oxidation of phthalic acid, and the other is due to the oxidation of water, which is the same as the blank photocurrent. Our experimental results showed that the blank photocurrent was essentially constant for the given set of experimental

conditions. For a given time period, the charge passed for both cases can be obtained by integration of the photocurrent and blank photocurrent. The charge difference between the two cases is the net charge,  $Q$ , due to the photoelectrochemical oxidation of phthalic acid, which is indicated as the shaded area in Fig 8. The net charge,  $Q$ , was measured by integration of net photocurrent within the degradation period as described in Fig 8. As predicted by Eqn. 3,  $Q$  is directly proportional to concentration (see Fig. 9). In this case, the slopes of the  $Q$ - $C$  curves (sensitivity) were dependent only on the number of electrons transferred ( $n$ ). The results in Fig. 7 and 9 (having conformed to theory) demonstrated the possibility of further developing the proposed system into a "universal" detection system for individual analytes.

The possibility of applying the proposed method for determining aggregate properties such as COD was also tested. We chose the APHA COD standard test solution (potassium hydrogen phthalate (KHP)) and a synthetic mixture with known COD values as our test solutions. Fig 10 shows the correlation between the experimental COD values (according to equation 7) and standard COD values. Excellent agreements between the two COD values were obtained in both cases.

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#### **Real Waste water Samples.**

Fourteen (14) different wastewater samples were collected from various industries in Queensland, Australia. After appropriate dilution, all samples were subject to the COD analysis using our method and standard COD method. The COD values obtained from the two methods for all

samples were then correlated and shown in Fig 11. A correlation coefficient of 0.973 and slope of 0.992 were obtained. This means our method predicts the same COD value as the standard COD method. This demonstrates that our method is equivalent to the standard method in predicting the COD values.

**Conclusion.** A novel COD analysis method has been developed, which is sensitive, environmentally friendly, robust, rapid and easy to be automated. This method in principle measures the theoretical COD value due to the extraordinary high oxidation power of photogenerated holes. Experimentally it correlated well with conventional dichromate method (Standard method). The electrode has a very good long time-stability, it had been used for more than a month without showing any decline of photocatalytic activity. The method described here is an absolute method and because the nature of photocatalytic reaction, the temperature has a little influence on the photocatalytic reaction rate, and has no influence on the exhaustive photoelectrolysis charge. The method shows a good tolerance to temperature change in contrast to Karube's method. During the experiment the temperature did not controlled with the sample temperature ranging from 10 to 40°C, no photocurrent and charge change was observed.

Whilst the description of the invention utilises a three electrode photochemical cell it will be appreciated that the photoelectrochemical cell may comprise a working electrode ( $\text{TiO}_2$ ) and a counter electrode, wherein the counter electrode may suitable act as both a counter electrode and a reference electrode. Furthermore it will also be appreciate that the working electrode may be formed from any nanoparticulate semiconductive film capable of photooxidation of organic compounds.

The current inventors have surprisingly found that the methods described above, utilising photoelectrochemical properties of  $\text{TiO}_2$  nanoparticle semiconductive electrodes provide for the direct determination of COD analysis. For their method, the accuracy is relied on the two oxygen electrodes, which have to be identical in responding to the oxygen change. In addition, their method cannot be used for low COD samples due to the

insufficient sensitivity of the method. There are many other disadvantages of their method, which makes the practical application of the method very difficult.

5 Throughout the specification the aim has been to describe the preferred embodiments of the invention without limiting the invention to any one embodiment or specific collection of features.

10 Throughout this specification, unless the context requires otherwise, the word "comprises", and variations such as "comprise" or "comprising", will be understood to imply the inclusion of a stated integer or group of integers or steps but not to the exclusion of any other integer or group of integers.

DATED this fourth day of April 2003.

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